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INFLUENCE OF BULK TURBULENCE AND ENTRANCE BOUNDARY LAYER THICKNESS ON THE CURVED DUCT FLOW FIELD*

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INTRODUCTION

The objective of this investigation was the experimental evaluation of bulk turbulence and boundary thickness influence on the secondary flow development in a square, 90° turning duct. A three-dimensional laser velocimetry system was utilized to measure the mean and fluctuating components of velocity in the large curved duct facility developed under NASA Contract NAS3-23278. The entrance flow field was conditioned by a combination of increased inlet duct length and square bar turbulence generators. The results from this investigation, with entrance boundary layer thickness of 20-percent and bulk turbulence level of 6-percent, were compared with the thin boundary layer results documented in NASA CR-174811 (Ref 1.).

The three-dimensional development of the viscous shear layers in the curved duct has a strong influence on the complete flow field. Since ducted three-dimensional flows are found in many engineering applications, including gas turbine engines, and contain high turbulence levels and high wall heat transfer rates, they present a difficult challenge to computational fluid mechanics codes. Turbulence modeling remains one of significant constraints to CFD advances due to inadequate physical understanding and experimental definition of turbulent shear flows.

The results of this investigation expand the curved duct data base to higher turbulence levels and thicker entrance boundary layers. The experimental results provide a challenging benchmark data base for computational fluid dynamics code development and validation. The variation of inlet bulk-turbulence intensity provides additional information to aid in turbulence model evaluation.

FACILITY AND INSTRUMENTATION

The experimental facility features modular tunnel components which allow flow measurements every 15° in the 90° bend and at one duct width upstream and downstream of the bend. The 25.4 cm (10 in) square cross-section tunnel is constructed with 13 to 1 area-ratio bell mouth contoured to provide a uniform flow. An additional four duct widths of entrance duct length were fabricated and installed to provide the

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additional boundary layer thickness. Two square-bar turbulence generator grids were fabricated and tested for flow quality and level of turbulence intensity. A 42 percent blockage grid was selected for the experimental investigation, and it produced an average turbulence intensity of 8-percent, two duct widths downstream and 6-percent, three duct widths downstream of the grid. Reference 2. provided the primary design data for the square bar grids. During the turbulence grid evaluation the curved duct static wall pressures were recorded to evaluate gross flow-field changes by comparison with previous wall pressure data. No significant wall pressure changes were observed.

The primary instrumentation was a three-component laser velocimeter which utilized two color beams and Bragg diffraction beam splitting/frequency shifting to separate the three simultaneous, orthogonal, velocity components. The laser velocimeter signal processors determine the values of velocity from water droplet seed particles crossing the moving fringe probe volume. The data is processed on-line by a minicomputer to yield real time values of mean and fluctuating velocity components, see Ref 1 for a complete description of the LV system. To assure data quality the laser velocimetry data was compared with pitot probe and hot-wire anemometer measurements in the entrance region.

EXPERIMENTAL INVESTIGATION

With the 42 percent blockage turbulence grid located three tunnel widths upstream of the entrance measurement station, detailed velocity surveys were conducted at six stations $(-1D, 0^\circ, 30^\circ, 60^\circ, 90^\circ, +1D)$. All data was taken at one Reynolds number corresponding to a tunnel bulk velocity of 10 meters/sec. At this test condition the wall boundary layers are fully turbulent ahead of the turbulence grid, and behind the grid typical wall turbulence levels of 10-15 percent remained with a core flow bulk turbulence of 6-8 percent.

The orthogonal laser velocimeter data was processed to yield mean velocity components U, V, W and the fluctuating components $u'v'w'$ calculated from the standard deviation on U, V, W. A minimum of 300 data samples was acquired for each flow field point. Data for each measurement station was acquired by computer controlled precision mill-bed traverse. All data was corrected to standard test conditions and nondimensionalized on duct bulk velocity.

This baseline set of data contains the influence of both thicker entrance boundary layer and bulk turbulence. To evaluate the separate influence of the thicker boundary layer on the downstream flow development, the 60° station was measured without the grid installed. The two sets of data for the 60° station contain the separate influences of boundary layer thickness and bulk turbulence.

DATA PRESENTATION AND DISCUSSION

Due the limited space in this paper, only the data from the 60° station will be presented. First it should be noted that both sets of data have very similar flow characteristics, thus the general flow field described by Taylor, Whitelaw, and Yianneskis in reference 3 has not been invalidated by addition of the turbulence grid. Figures 1 and 2 present respectively the axial velocity profiles for the thick boundary layer and thick boundary layer with bulk turbulence. Away from the wall shear layers, the nearly linear velocity gradient across the duct is nearly identical for both flows. The major axial velocity differences occurs in the strong viscous interaction region along the inner wall. The axial velocity results from this investigation and thin boundary layer investigation (Ref 1.) are nearly identical outside of the strong viscous wall interaction region. To satisfy continuity higher center-line velocities are associated with the thicker wall boundary layers. The secondary flow velocities V and W are much more sensitive to the entrance region boundary layer thickness.

The crossflow velocity vector plots for the 60° station show clearly the strong influence of boundary layer thickness on the magnitude of the crossflow velocity (Fig. 3 and 4.) The larger natural turbulent boundary layer produces a strong crossflow development with the "vortex" center located farther from the duct walls. The increased crossflow velocities may be related directly to the axial momentum deficit entering the curved duct. When the turbulence grid is introduced into the developing turbulent boundary layer, the boundary layer is partially re-energized resulting in reduced cross flow velocities as shown in figure 4.

The turbulence intensity distributions for the 60° station are compared in figures 5 and 6. The bulk levels of turbulence at the entrance station were 3 percent and 6 percent respectively for these two flows. The bulk turbulence level has decayed to 4-percent from a level of 8-percent just behind the grid as shown in Figure 6.

The results of this investigation are consistent with the turbulent transport of momentum models. The increase in entrance bulk turbulence from 3-percent to 6-percent has a significant influence on the axial velocity and crossflow development in the curved duct. The wall turbulence intensity and distribution matches the axial shear layer distribution and correlates well with the crossflow velocities, figures 1, 2, 3, 4, 5, and 6.

A complete summary of the data from this investigation has been documented in a NASA report soon to be published and distributed to the HOST participants. This report compares and analyzes the results from both the thick and thin entrance boundary layer investigations and expands the experimental benchmark data base for curved duct flows.

REFERENCES

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3. Taylor, A.; Whitelaw,J.; and Yianneskis, M.: Measurements of Laminar and Turbulent Flow in a Curved Duct with Thin Inlet Boundary Layers. NASA CR 3367, 1981.

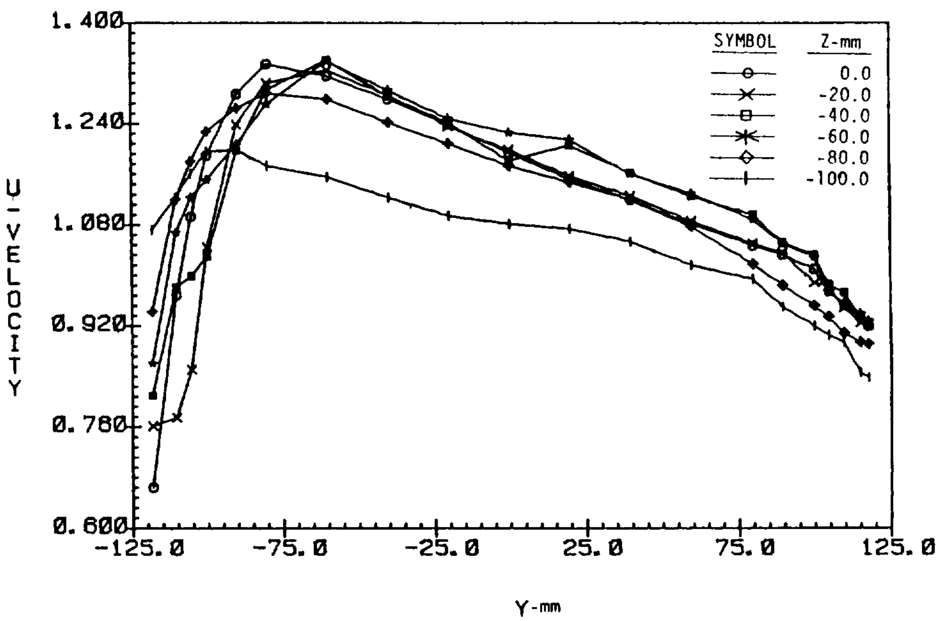

FIGURE 1. AXIAL VELOCITY, 60" STATION THICK TURBULENT BL NO GRID

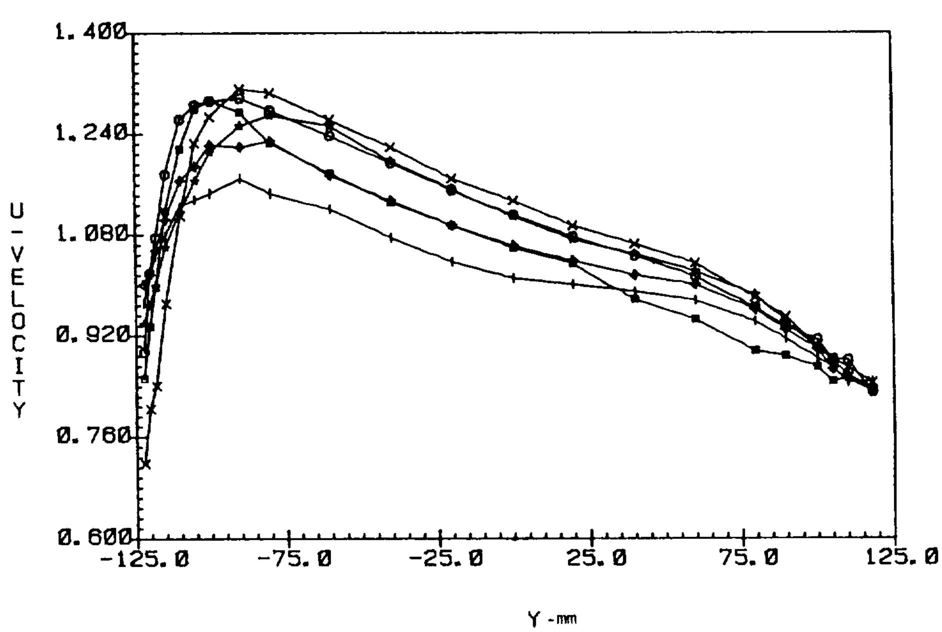

FIGURE 2. AXIAL VELOCITY, 60" STATION THICK TURBULENT BL WITH GRID

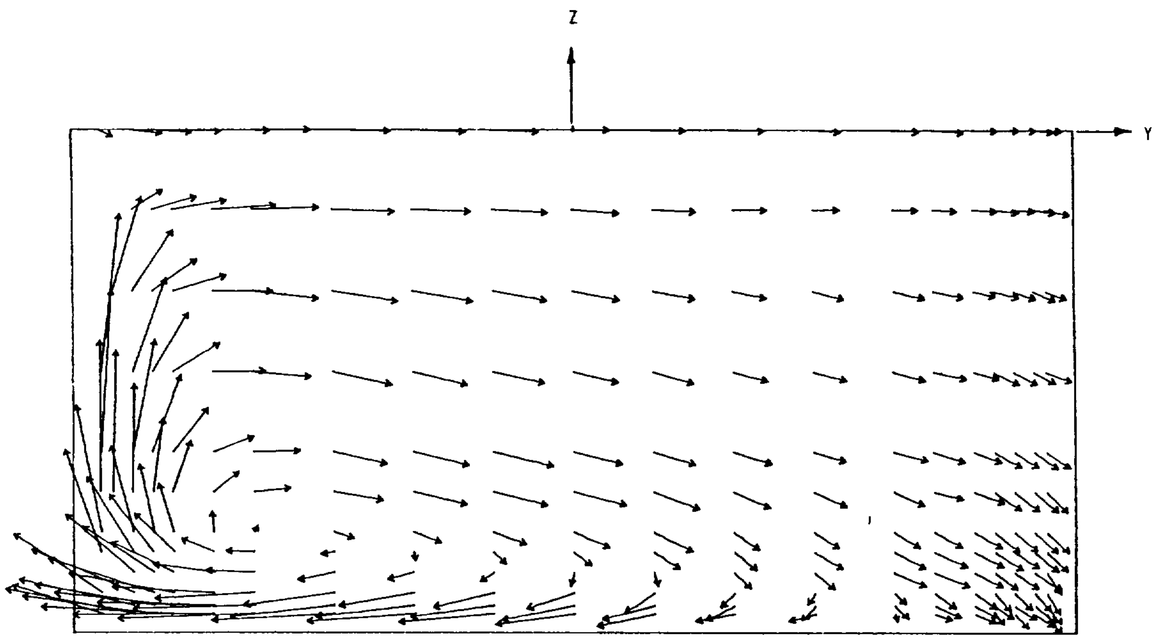

FIGURE 3. CROSS FLOW VELOCITY, 60° STATION THICK TURBULENT BL
NO GRID

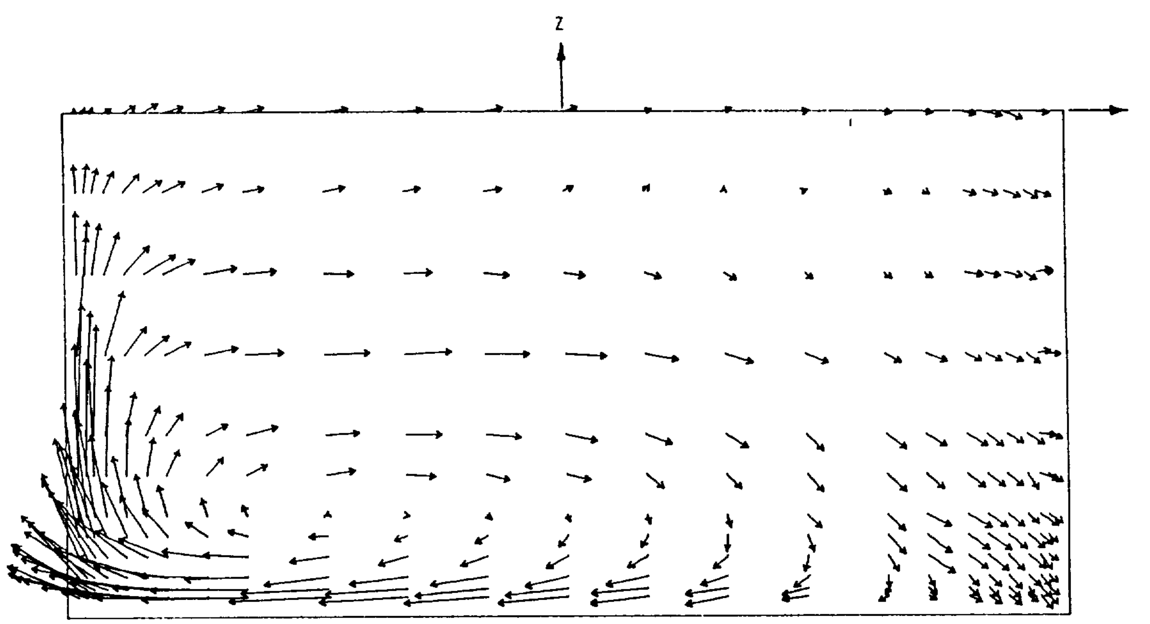

FIGURE 4. CROSS FLOW VELOCITY, 60° STATION THICK TURBULENT BL
WITH GRID

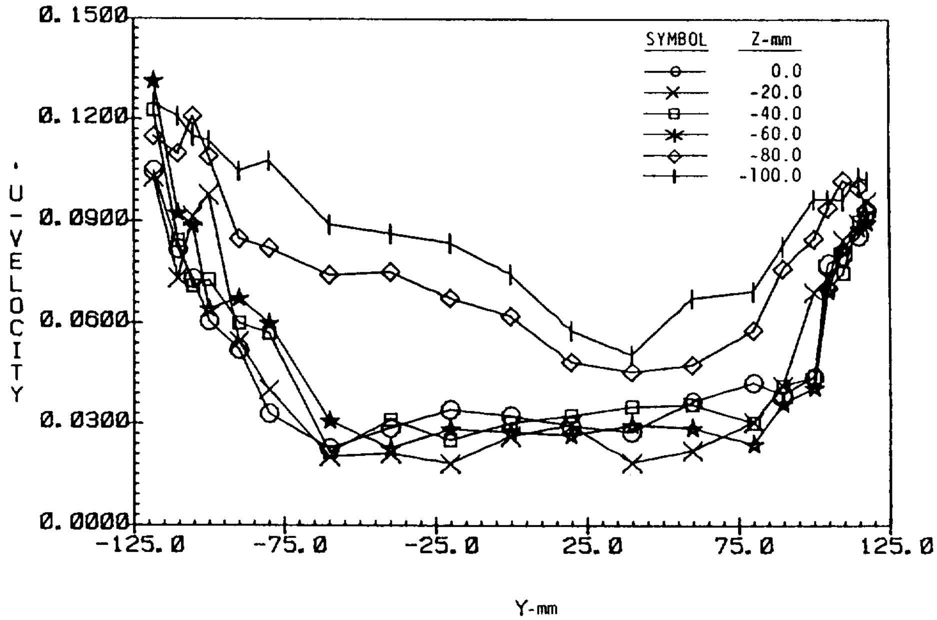

FIGURE 5. AXIAL TURBULENCE INTENSITY, 60° STATION THICK TURBULENT BL NO GRID

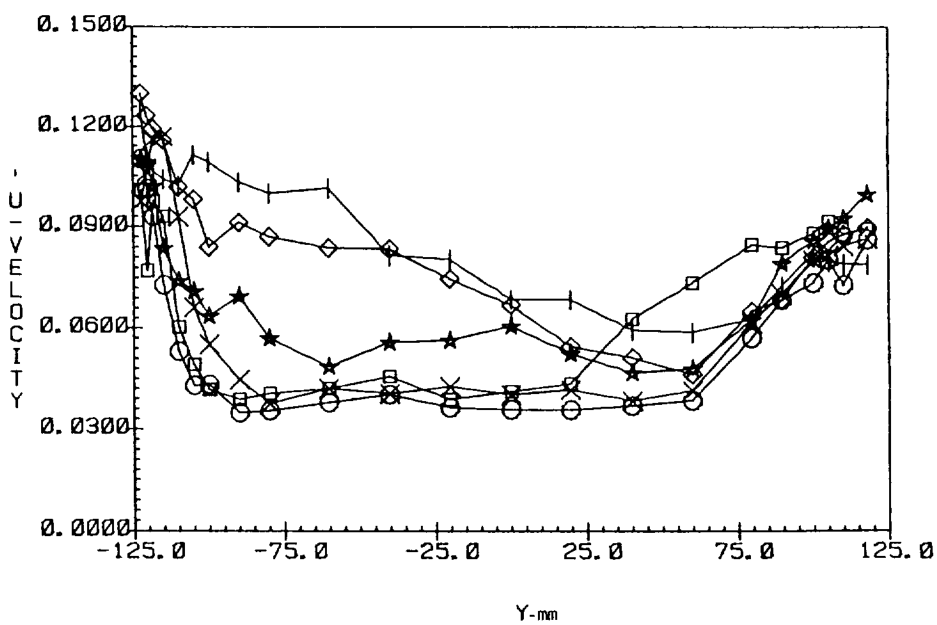

FIGURE 6. AXIAL TURBULENCE INTENSITY, 60° STATION THICK TURBULENT BL WITH GRID